EXPERIMENTAL INVESTIGATION OF THE HYDRODYNAMIC BOUNDARY LAYER AND HEAT TRANSFER ON A STATIONARY DISK WITH RADIAL-SLIT AIR INJECTION

K. A. Vezlomtsev and S. I. Morozov

Inzhenerno-Fizicheskii Zhurnal, Vol. 13, No. 3, pp. 308–313, 1967

UDC 532.517.4

This paper gives the main results of an experimental investigation of the laws of flow and heat transfer for the case of a turbulent jet emerging from a radial source of finite dimensions and spreading along a wall in the Re_x range 10^4–$2 \cdot 10^5$.

Klientov [1] obtained a theoretical solution of this problem in the general form by using approximate integral relationships and the condition of nontriviality of the solution of the hydrodynamic problem, established by Akatnov [2] for a plane semi-infinite laminar jet and by Tsukker [3] for a semi-infinite radial laminar jet. It was assumed that the radial jet emerges from a point source situated in the plane wall, along which the jet spreads. The only experimental investigations in this field are Abramzon and Skovorodnikov's measurements [4] of the velocity profiles for radial semi-infinite jets in the Re range $1.3 \cdot 10^4$–$2.8 \cdot 10^4$.

The experimental investigation was conducted on a special apparatus (Fig. 1). Its working section was a smooth textolite-glass disk calorimeter of composite construction and diameter 440 mm. The disk calorimeter contained the main dc electric heater, consisting of four segmented nichrome sections connected in parallel and having a total resistance of 27 ohms. Each section consisted of a spiral of nichrome wire accommodated in annular grooves. The resistance of the sections over the radius of the disk was chosen to ensure constancy of the specific heat flux: q = const. The thickness of the wall between the heat-transfer surface and the inner annular surface under the nichrome spiral was 2 mm. The disk calorimeter was fitted to a textolite-glass cover disk 15 mm thick. The power of the main electric heater was measured with class-0.5 instruments.

The temperature of the heat-transfer surface was measured by ten copper-constantan thermocouples with thermoelectrodes 0.2 mm in diameter. The thermocouples were fastened with a special adhesive to circular grooves 0.3 mm deep at 20-mm steps over the radius of the disk. The adhesive was made from textolite-glass powder and BF-6 cement. The emf of the thermocouples was measured by PP potentiometers with an instrumental error of 0.05 mV.

The cooling air was brought to the disk through a normal nozzle flowmeter to a directing nozzle with a smooth outlet. The directing nozzle and the disk surface formed a radial slit source with an initial uniform velocity distribution over the slit width. Diagrams of the radial velocities on the disk were measured by means of a single-channel total-pressure tube with a positioning device and an MMN micromanometer. This device enabled us to position the inlet nozzle of the total-pressure tube at any point on the disk to within 0.05 mm in the axial direction and to within 1 mm over the disk radius. The thickness of the nozzle was 0.5 mm, which enabled us to measure the kinetic head at a minimum axial distance of 0.3 mm from the disk.

Heat loss from the surface of the cover disk was compensated for by means of an adjustable ac electric heater. Possible heat leakage to the center of the disk calorimeter and through the cover disk was determined from the readings of 12 thermocouples imbedded in the disk at different radii and from the known thermal conductivity of textolite-glass. Three thermocouples were mounted on the rim of the disk. The relative humidity of the air was monitored by a sensor connected to an electronic recorder.

During the experiments we altered the geometric characteristic b_0/r_0 of the slit source from 0.0212 to 0.1 by changing the slit width b_0 from 0.85 to 4 mm. The radius of the outflow was constant, equal to 40 mm. The initial velocities at the outlet of the slit source varied from 20 to 100 m/sec, which corresponds to $Re_0 = 10^3$–$1.2 \cdot 10^4$.

The temperature on the disk surface in the experiments was 60–100° C. The temperature of the cooling air was −20 to −25° C. The total heat leakage in the experiments did not exceed 3–5% of the total heat produced by the main heater.

From measurements of the kinetic heads, the heat flow, and temperatures, we calculated the velocities and heat-transfer coefficients by the usual methods. In the determination of the physical parameters of the air the characteristic quantity was the mean temperature of the boundary layer

$$t = \frac{t_s + t_f}{2}. \quad (1)$$

The results of measurement of the velocity profiles on different radii of the disk in generalized coordinates $w/w_m = f(y/y_c)$ are shown in Fig. 2. As the figure shows, the experimental data agree satisfactorily with one another. The scatter of the points does not exceed 5%.

It can be shown that these data are approximated by a modified Karman profile for the radial velocity component on a disk rotating in an unbounded volume. For this it is better to reduce the Karman profile

$$w = 0.162 \omega r \left(\frac{y}{b}\right)^{\frac{1}{7}} \left(1 - \frac{y}{b}\right) \quad (2)$$

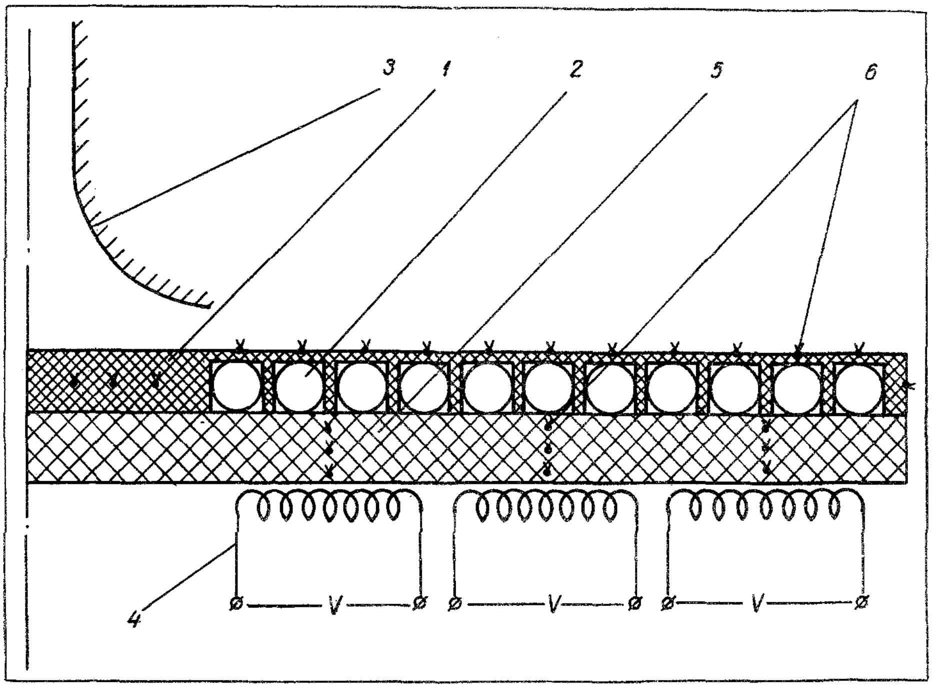

Fig. 1. Working section of the experimental apparatus: 1) disk-calorimeter; 2) main electric heater; 3) guide nozzle; 4) compensating heater; 5) cover disk; 6) copper-constantan thermocouples.

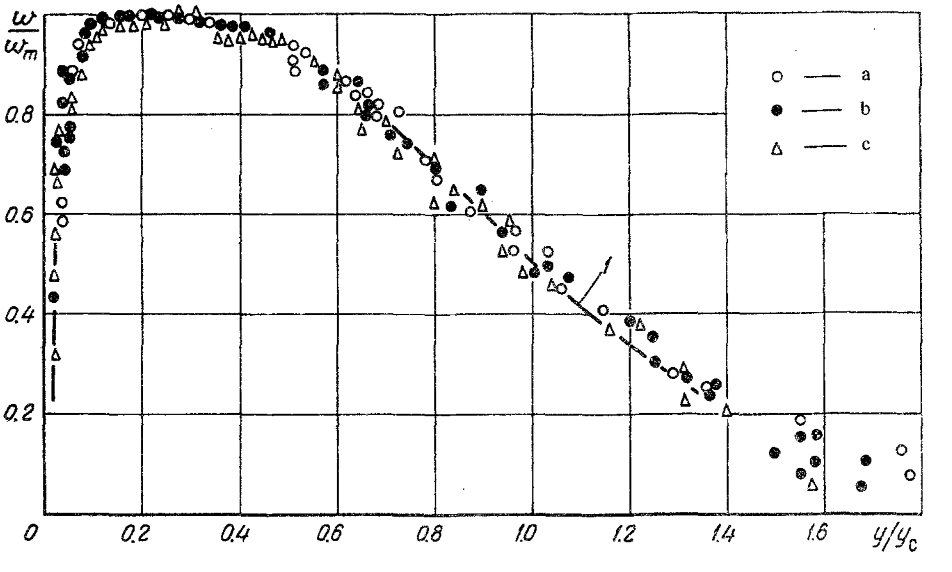

Fig. 2. Results of measurement of velocity profiles on different radii of the disk: 1) from formula (8). Authors' experimental data: a) for $b_0 = 0.85$ mm; b) 1.5; c) 4.

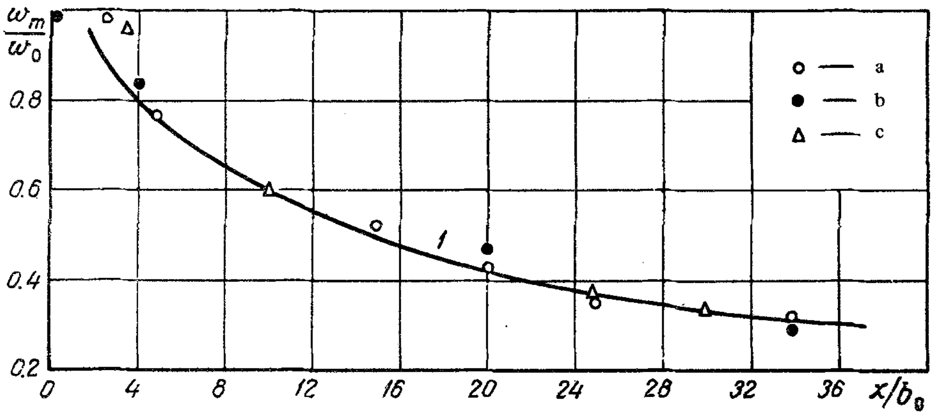

Fig. 3. Fall of the maximum radial velocity along the disk radius: 1) from formula (13) for $b_0 = 4$ mm. Authors' experimental data: a) $w_0 = 38.2$ m/sec; b) 31.2; c) 18.2.

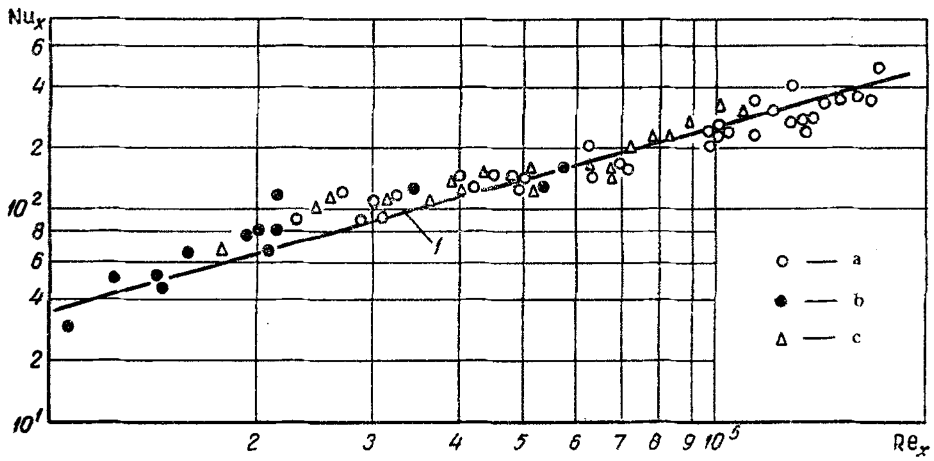

Fig. 4. Heat transfer of a stationary disk with radial-slit air injection: 1) from formula (14); a) for $b_0 = 1.5$ mm; b) 2.5; c) 4.

to coordinates $w/w_m = f(y/y_c)$, for which, equating the derivative of relationship (2) to zero,

$$\frac{\partial w}{\partial y} = 0.162\omega r \frac{\partial}{\partial y}\left[\left(\frac{y}{b}\right)^{\frac{1}{7}}\left(1-\frac{y}{b}\right)\right] = 0, \quad (3)$$

we determine the coordinate at which function (2) attains its maximum value. The solution is

$$y_m = 0.125b. \quad (4)$$

After substitution of (4) into (2), the expression for the velocity maximum takes the form

$$w_m = 0.106\omega r. \quad (5)$$

Dividing Eq. (2) by (5), we obtain

$$\frac{w}{w_m} = 1.525\left(\frac{y}{b}\right)^{\frac{1}{7}}\left(1-\frac{y}{b}\right). \quad (6)$$

When $w = 0.5w_m$,

$$y = y_c = 0.655b. \quad (7)$$

Hence, after replacement of b in Eq. (6) by y_c the expression for the Karman profile takes the form

$$\frac{w}{w_m} = 1.525\left(0.655\frac{y}{y_c}\right)^{\frac{1}{7}}\left(1-0.655\frac{y}{y_c}\right). \quad (8)$$

As Fig. 2 shows, relationship (8) satisfactorily describes the experimental data for a stationary disk swept by a jet.

From the experimental results the change in the coordinate y_c along the flow is given by the empirical relationship

$$y_c = b_0 + 0.06(r - r_0). \quad (9)$$

As an example, Fig. 3 shows the experimental data for the fall in maximum velocity along the disk radius. To determine the theoretical relationship for this characteristic of the jet we can use the conservation equation proposed by Akatnov and Tsukker. This equation for a source of finite dimensions is written in the following form:

$$E = \int_0^b rw^2\left(\int_0^y rwdy\right)dy = w_0^3 r_0^2 b_0^2 = \text{const}. \quad (10)$$

After substitution of (6), the equation is brought to the form

$$r^2 w_m^3 \int_0^b 1.525^2\left(\frac{y}{b}\right)^{\frac{2}{7}}\left(1-\frac{y}{b}\right)^2 \times$$

$$\times\left[\int_0^y 1.525\left(\frac{y}{b}\right)^{\frac{1}{7}}\left(1-\frac{y}{b}\right)dy\right]dy = w_0^3 r_0^2 b_0^2, \quad (11)$$

whence

$$\left(\frac{w_m}{w_0}\right)^3 = r_0^2 b_0^2 \Big/ \left\{1.525^3 r^2 \int_0^b \left(\frac{y}{b}\right)^{\frac{2}{7}}\left(1-\frac{y}{b}\right)^2 \times\right.$$

$$\left.\times\left[\int_0^y\left(\frac{y}{b}\right)^{\frac{1}{7}}\left(1-\frac{y}{b}\right)dy\right]dy\right\}. \quad (12)$$

After solution of the integrals, the expression for the maximum velocity component becomes

$$w_m = w_0 \sqrt[3]{\frac{r_0^2 b_0^2}{0.13 b^2 r^2}}. \quad (13)$$

As Fig. 3 shows, there is a satisfactory agreement between the calculated and experimental data over the whole disk. An exception is the initial region ($r - r_0 \le 10b_0$) on which the velocity diagram outside the boundary wall layer is of a linear nature with practically constant velocity [5]. Owing to the smallness of the dimensions of the initial region in comparison with the disk, this region can be neglected in a first approximation, and the value of the maximum velocity can be calculated using relationship (13).

The heat-transfer conditions on a disk with its whole surface swept by a radial jet are similar to the case of heat transfer of a flat plate swept by an unbounded flow with variable velocity over the disk $w_\infty = f(x)$ in the absence of a pressure gradient. Hence, in the generalization of the experimental heat-transfer data, we took the velocity w_m along the characteristic length $x = r - r_0$ as the characteristic velocity in the Reynolds number.

The obtained experimental data for the local heat transfer of the disk are presented in Fig. 4. As the figure shows, within the limits of experimental accuracy, the experimental data agree satisfactorily with one another, and in the Re_x range 10^4–$2 \cdot 10^5$ are described by the relationship

$$Nu_x = 0.0245 Re_x^{0.8}. \quad (14)$$

In the region of $Re_x = 10^4$–$3 \cdot 10^4$, the experimental data are 8–12% higher than the approximating line. This is due to the fact that most of the points in the indicated Re_x range characterize the heat transfer in the initial region of the outflow. The Reynolds number corresponding to these points is slightly underestimated, since formula (13) is only a first approximation of the change in the characteristic velocity w_m over the length of the initial region. Despite this, the obtained data are within the limits of error in the determination of the heat-transfer coefficients.

NOTATION

w_0 is the initial velocity of the outflow from the radial slit-source; w is the radial velocity on the disk; w_m is the local maximum radial velocity; y_c is the coordinate corresponding to the ratio $w/w_m = 0.5$ outside the boundary wall layer; b_0 is the width of the slit-source; r_0 is the initial radius of the outflow; r is the variable radius; b is the variable width of the jet over the disk radius; t_s is the wall temperature; t_f is the flow temperature; q is the specific heat flux; ν is the kinematic viscosity; λ is the thermal conductivity of air; $Nu_x = \alpha(r - r_0)/\lambda$ is the Nusselt number; $Re_x = w_m(r - r_0)/\nu$ is the Reynolds number; $Re_0 = w_0 b_0/\nu$ is the Reynolds number.

REFERENCES

1. N. V. Klientov, collection: Heat and Mass Transfer, Vol. 2 [in Russian], Nauka i tekhnika, Moscow, 1965.

2. N. I. Akatnov, Trudy Leningradskogo politekhnicheskogo instituta, no. 198, 1958.

3. M. S. Tsukker, PMM, 18, 1954.

4. L. S. Abramzon and Yu. A. Skovorodnikov, Trudy Nauchno-issledovatel'skogo instituta po transportu i khraneniyu nefti i nefteproduktov, no. 2, 1963.

5. G. N. Abramovich, Theory of Turbulent Jets [in Russian], Fizmatgiz, 1960.

23 November 1966